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Control Structural Interaction Testbed: A Model For Multiple Flexible Body Verification

M. A. Chory, A. L. Cohen, R. A. Manning, M. L. Narigon, V. A. Spector
TRW Space and Technology Group, Redondo Beach, CA

Abstract
Conventional end-to-end ground tests for verification of control system performance become increasingly more complicated with the development of large, multiple flexible body spacecraft structures. The expense of accurately reproducing the on-orbit dynamic environment, and the attendant difficulties in reducing and accounting for ground test effects limits the value of these tests.

TRW has developed a building block approach whereby a combination of analysis, simulation, and test has replaced end-to-end performance verification by ground test. Tests are performed at the component, subsystem, and system level on engineering testbeds. These tests are aimed at authenticating models to be used in end-to-end performance verification simulations: component and subassembly engineering tests and analyses establish models and critical parameters, unit level engineering and acceptance tests refine models, and subsystem and system level tests confirm the models' overall behavior.

The Precision Control of Agile Spacecraft (PCAS) project has developed a control structural interaction testbed with a multibody flexible structure to investigate new methods of precision control. This testbed is a model for TRW's approach to verifying control system performance.

This approach has several advantages: 1) no allocation for test measurement errors is required, increasing flight hardware design allocations, 2) the approach permits greater latitude in investigating off-nominal conditions and parametric sensitivities and 3) the simulation approach is cost effective, because the investment is in understanding the root behavior of the flight hardware and not in the ground test equipment and environment.

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Introduction

Conventional end-to-end ground tests for verification of control system performance become increasingly more complicated with the development of large, multiple flexible body spacecraft structures. These future generations of NASA and DOD spacecraft will require a high level of agility and precision in line-of-sight pointing. In addition, many missions will have multiple gimbaled payloads that must maintain precise pointing despite large maneuvers of the main spacecraft and other appendages. Dynamic range and bandwidth considerations demand a dimensionally stable structure with multiple overlapping control systems. The expense of accurately reproducing the on-orbit dynamic environment, and the attendant difficulties in reducing and accounting for ground test effects limits the value of end-to-end tests.

Conventional spacecraft design techniques in the areas of structures, materials, and control systems are incapable of meeting these future space mission requirements. Improvements are required in all areas, and the new approaches need to be integrated and verified. In particular, an integrated design process is needed in order to exploit the potential synergy among the disciplines while minimizing mission risk due to harmful control/structural interactions.

TRW has developed a method of coordinated control/structural design that has been used to deal with large, structurally complicated spacecraft. This approach involves a combination of analysis, simulation, and test to coordinate the design of the control system and structure. This methodology has two effects: it leads to a truly integrated design process where required, and it reduces the reliance on end-to-end ground test for performance verification.

Instead of an end-to-end ground test, tests are performed at the component, subsystem, and system level on engineering testbeds. These tests are aimed at authenticating models to be used in end-to-end performance verification simulations: component and subassembly engineering tests and analyses establish models and critical parameters, unit level engineering and acceptance tests refine models, and subsystem and system level tests confirm the models' collective behavior.

This verification approach has several advantages: 1) no allocation for system test measurement errors is required, increasing flight hardware design allocations, 2) the approach permits greater latitude in investigating performance under off-nominal conditions and parametric sensitivities and 3) the simulation approach is cost effective, because the investment is in understanding the root behavior of the flight hardware and not in the ground test equipment and environment. In addition, the simulation is a very effective requirements allocation and verification tool.

The Precision Control of Agile Spacecraft (PCAS) Independent Research and Development project has developed a control structural interaction testbed with a multibody flexible structure to investigate new methods of precision control. The test article is an 18-foot long space truss mounted on an air bearing so that it is free to slew over a 60-degree arc. Attached to the truss is a flexible appendage system for study of multiple body interactions. The project also includes testbed control equipment and measurement instrumentation. TRW's design and verification approach has been used on this testbed..

This paper will briefly describe TRW's approach to multiple flexible body design and verification. The coordinated design and verification methodology used in the development of the control system and the performance simulation will be discussed. The control structural interaction testbed, results obtained from design work, and tests performed to date will be summarized.

Motivation/History

TRW has been a major developer and integrator of space vehicles for over 30 years. A methodology for coordinated control/structural design and verification for complicated satellite systems (large and structurally rich) has evolved over the years that has proven to accurately predict on-orbit performance. The approach does not require end-to-end performance testing but relies on a carefully constructed performance simulation with models authenticated by appropriately defined tests. The extension of this methodology for future large space structures that require state-of-the-art structure design is possible with the use of a control structural interaction testbed.

Testbed facilities are widely used in the study of active control of flexible structures (Reference 1). TRW's testbed design is a natural evolution of years of work in the control structural interaction (CSI) arena (References 2-20). Figure 1 is a summary of TRW's technology heritage regarding CSI.

The testbed design was influenced by TRW's approach to design and verification of large space structures. The testbed embodies the characteristics of and has performance metrics traceable to future agile spacecraft missions. It can be used to verify simulation tools and models and is easily reconfigurable to specific projects.

The Coordinated Design Process

Conventional spacecraft design techniques are based on the independent design of the control and structure subsystems (see Figure 2). Usually the structure is designed with little or no regard for either adverse control/structural interactions or beneficial control/structure synergy. A control system (i.e., sensors, actuators, and control laws) is then designed for the predefined structure, using at most mode separation and mass property information. This approach has been successfully employed on many past spacecraft where mission requirements permitted generous separation between structural frequencies and control bandwidths.

The trend toward simultaneous requirements of large size, light weight, rapid slew, and precision pointing precludes designs that rely solely on control/structure frequency separation. Also, a predetermined structure may unduly restrict the type and location of control sensors and actuators. Iterating the independent structure/control design procedure may, depending on the requirements, finally lead to an acceptable design. However, for demanding missions, the independent design procedure will usually lead to a spacecraft that is far from optimal in terms of weight, size, power, performance, robustness, and design/production cost.

TRW currently implements a coordinated approach to control/structure design (see Figure 3.) This approach combines design information and requirements to blur the traditional separation between the structure and control design. The structure is designed not only to meet loads

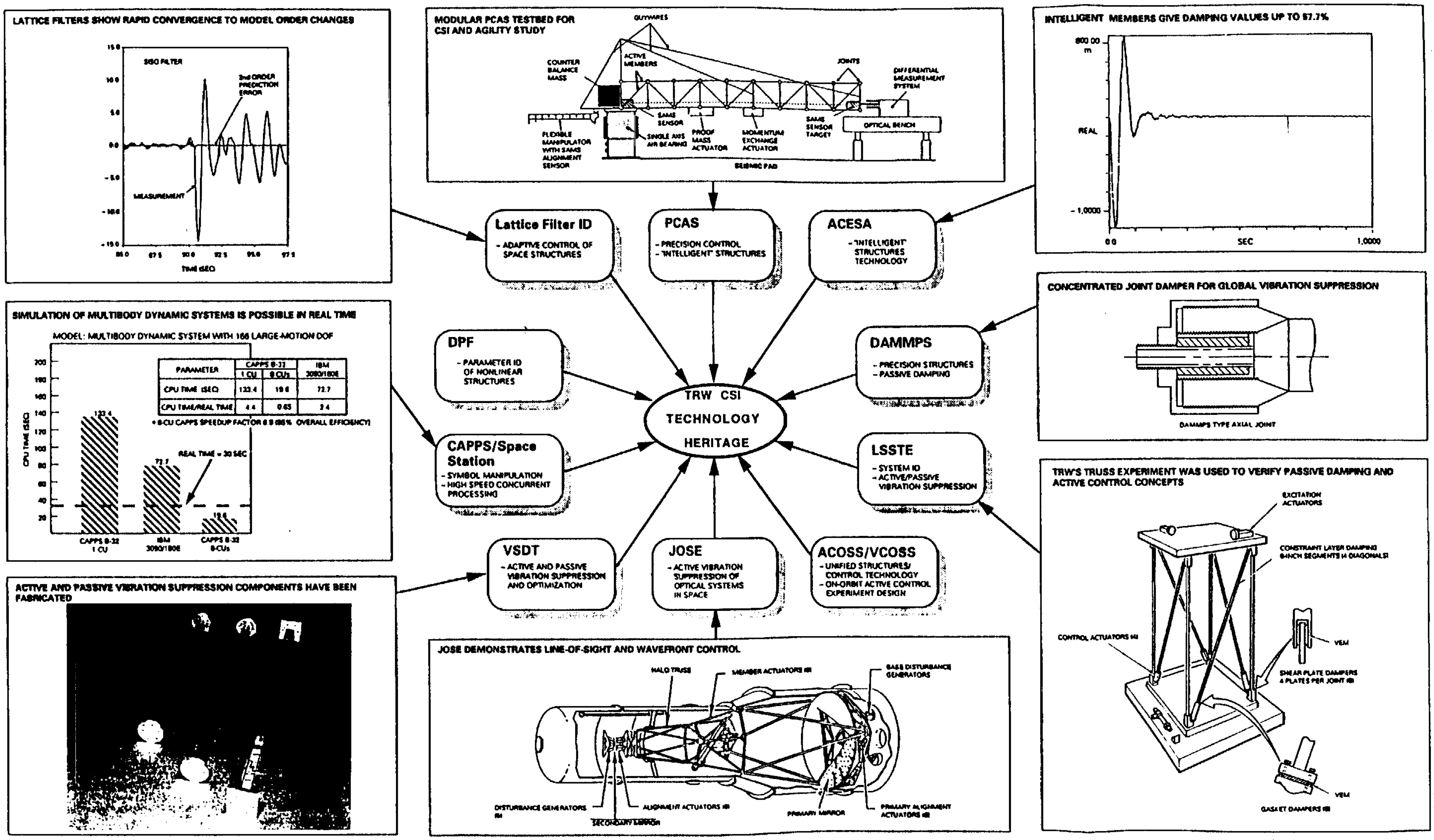

Figure 1.TRW's CSI Technology Heritage

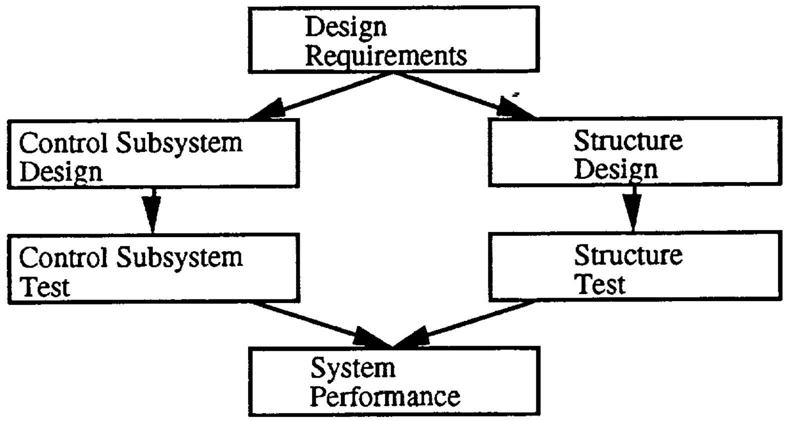

Figure 2. Independent Design

requirements (i.e., stowed loads or stowed stiffness requirements), but also stiffness requirements levied by the control subsystem so that system performance and stability is assured. This approach also is a natural step to an integrated design, where not only is the structure designed so that the control subsystem can meet its performance requirements, but also that the structure subsystem depends on control subsystem performance to meet its design requirements (see Figure 4.) Integrated design opens up a range of new options and approaches. For example, in the independent design process, the structure is often designed to achieve a specific first modal frequency, based on structure/control frequency separation. Total system weight could be reduced, however, by combining active shape control with the structural design to achieve the required total stiffness. In some cases, neither the passive structure nor the active control alone can meet the stiffness requirements, but together they do. Likewise, bandwidth and robustness of the attitude control loops can be increased by incorporating active or passive damping into the structure.

Figure 5 shows a more detailed view of the control system design process with coordinated structural design. Structure/control design iterations are performed concurrently, rather than sequentially. In this way, detrimental interactions can be identified and avoided prior to the fabrication of the flight hardware. Figure 6 shows the concurrent control/structure design process to determine structural stiffness requirements needed for acceptable pointing performance. Once these initial requirements are established, changes to the stiffness requirements resulting from detailed analysis or component tests follow the process shown in Figure 7.

Referring again to Figure 5, this coordinated design process results in the development of a performance simulation that incorporates models of all significant effects, including structural dynamics, control and sensor dynamics, control law implementation, and models of the system environment. This performance simulation is the tool used to assess requirements allocation and design changes, and to incorporate information from component and breadboard/brassboard tests.

The Verification Process

This coordinated design approach has two effects: it leads to a truly integrated design approach where required, and it reduces the reliance on end-to-end ground test for performance verification. Because both the coordinated and the integrated design approach rely on a system simulation for assessment of the design, it is a natural progression to rely on the simulation to

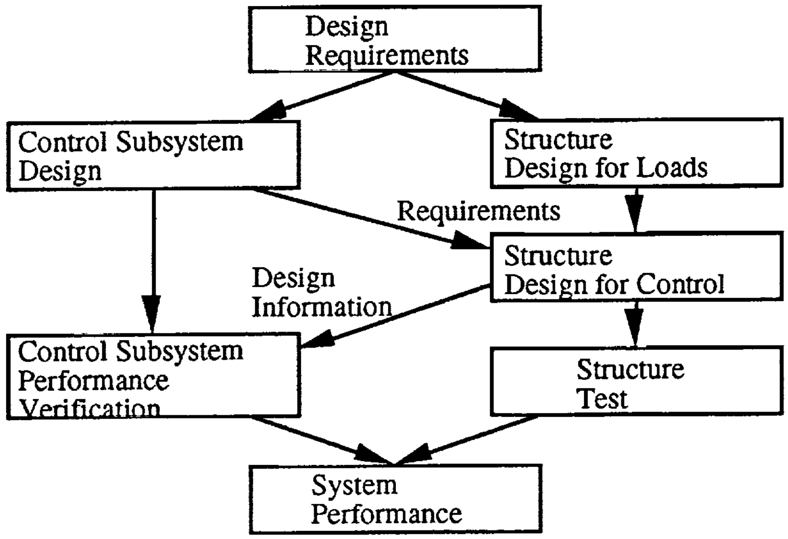

Figure 3. Coordinated Design

support formal verification of the system performance. TRW defines the verification activity as the series of steps taken to show that a design meets its requirements. The validation activity is the series of steps that show the the requirements are consistant.

Three aspects have to be considered: unit (subsystem, box, slice) interface verification, performance verification, and functional validation. Interface verification is the process of determining that the unit meets it interface requirement as specified in the unit specification. For example, this is routinely determined as part of the box acceptance test and is verified at the system level during box integration onto the spacecraft. Performance verification proves that the parameter to be verified satisfies performance specifications. Examples of such elements for an attitude control subsystem include pointing accuracy, jitter, attitude determination accuracy, etc. The final aspect is functional validation, which is the demonstration that the elements function as assumed in various verification processes.

TRW's verification philosophy and design approach are complementary. Functional validation is achieved by early integration of breadboard and engineering models into a hardware-in-the-loop testbed. This provides early checkout of hardware and hardware-software interfaces and validates the overall system model used in the performance simulation. The performance verification is provided by the end-to-end performance verification simulation whose models are anchored by component, assembly, and system level tests.

Functional operation of the system is determined with hardware-in-the-loop tests. These tests help to anchor the performance simulation and assess the implementation of the functional requirements in the flight hardware and software. Figure 8 shows the arrangement of equipment in a hardware in the loop test. In the 1960's and 1970's TRW performed Moving Base Tests to verify the operation of the spacecraft attitude control subsystem. The spacecraft sensors, actuators, and control electronics were mounted on an air bearing so that the entire assembly was free to move in response to the thrusters or reaction wheels. The spacecraft hardwired logic would respond to this motion and the response would be compared to the results predicted by

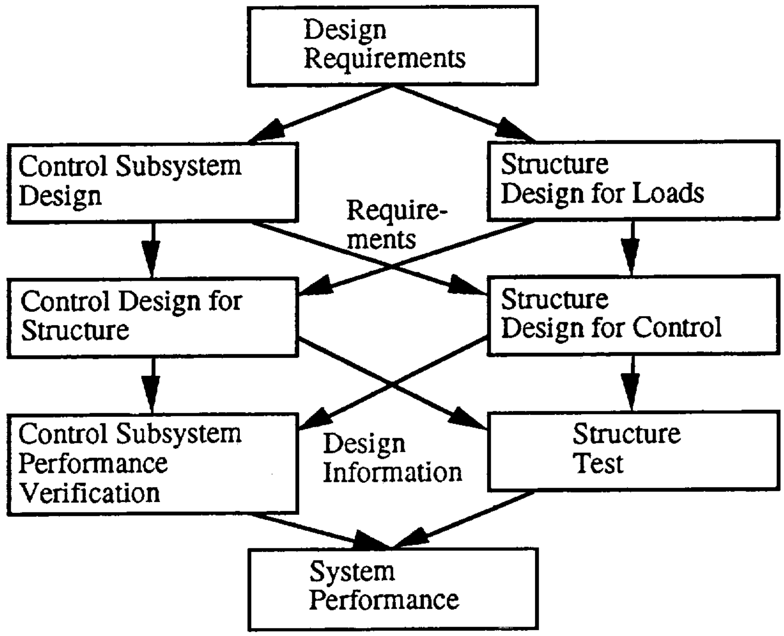

Figure 4. Integrated Design

analysis. These tests verified attitude control subsystem operation as implemented in the logic circuits and validated the mathematical modeling used to design the control laws.

Due to the expense and difficulty of accurately simulating the spacecraft motion and performance with larger spacecraft on an air bearing, Moving Base Tests were replaced by Fixed Base Tests, or hardware-in-the-loop tests. This was possible because a high degree of confidence in the mathematical modeling of rigid body dynamics exists after years of test validation and successful on-orbit performance. The hardware-in-the-loop tests use analog and digital computers together with interfacing electronics to sense control system actuator outputs and provide sensor inputs. The spacecraft components were not free to move, hence the name Fixed Base.

Sensed outputs are input to a computer where the resulting motion of the spacecraft is mathematically modeled. The simulated motion is used to determine the proper stimulation to be applied to the sensors. The simulation of the spacecraft motion was computationally demanding, resulting in the development of special hardware and software techniques to perform these functions. Increases in computer processing speed and reductions in cost have simplified the simulation process.

Because of increasingly complex attitude control subsystem performance requirements, the hardware-in-the-loop tests also changed from being a formal verification of the subsystem performance to an engineering development test. Realtime demands of the test made it impractical to put all the performance simulation fidelity into this test. The formal verification of the subsystem performance is by analysis and the performance simulation. The hardware in the

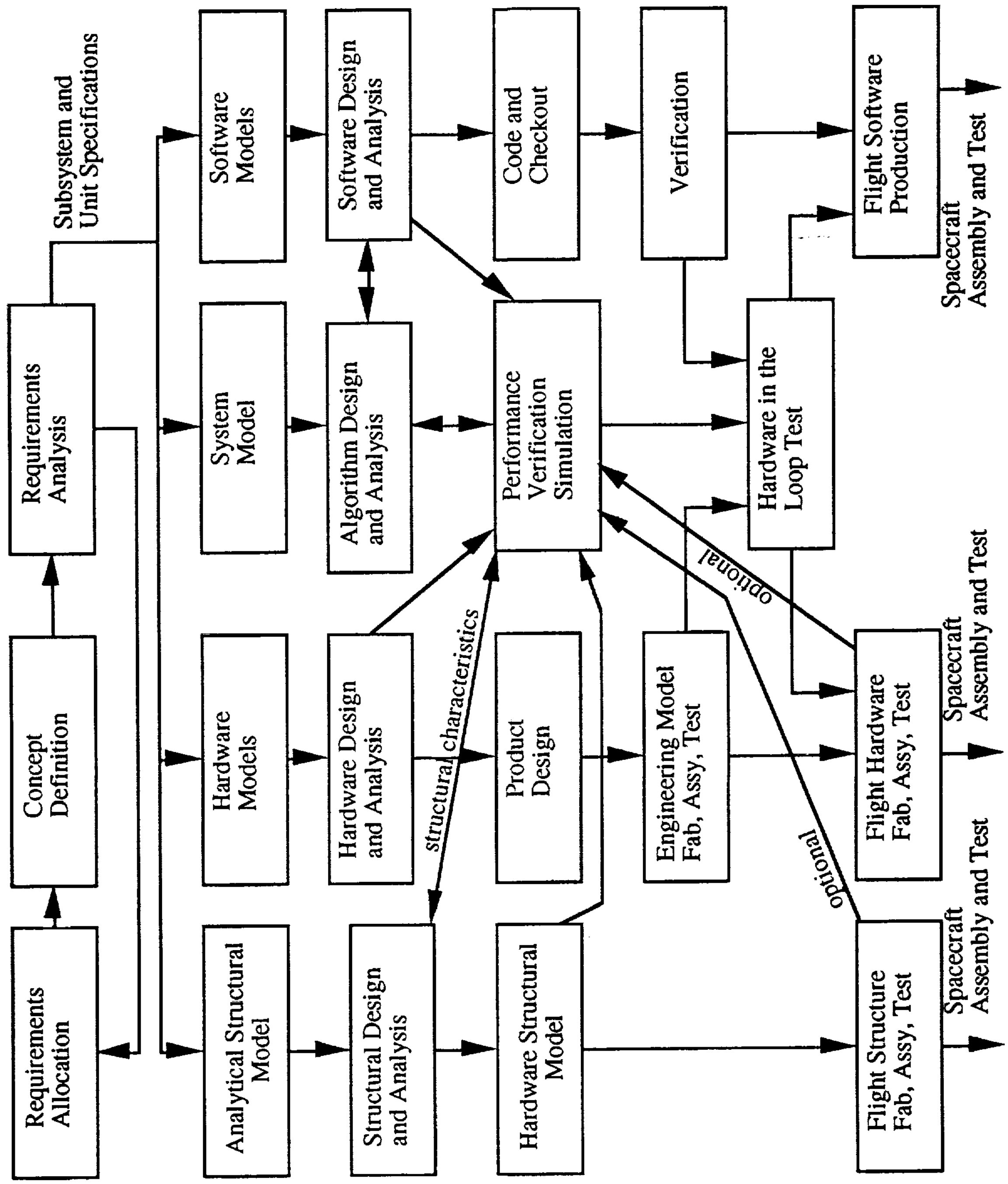

Figure 5. Control System Design Process with Coordinated Structural Design

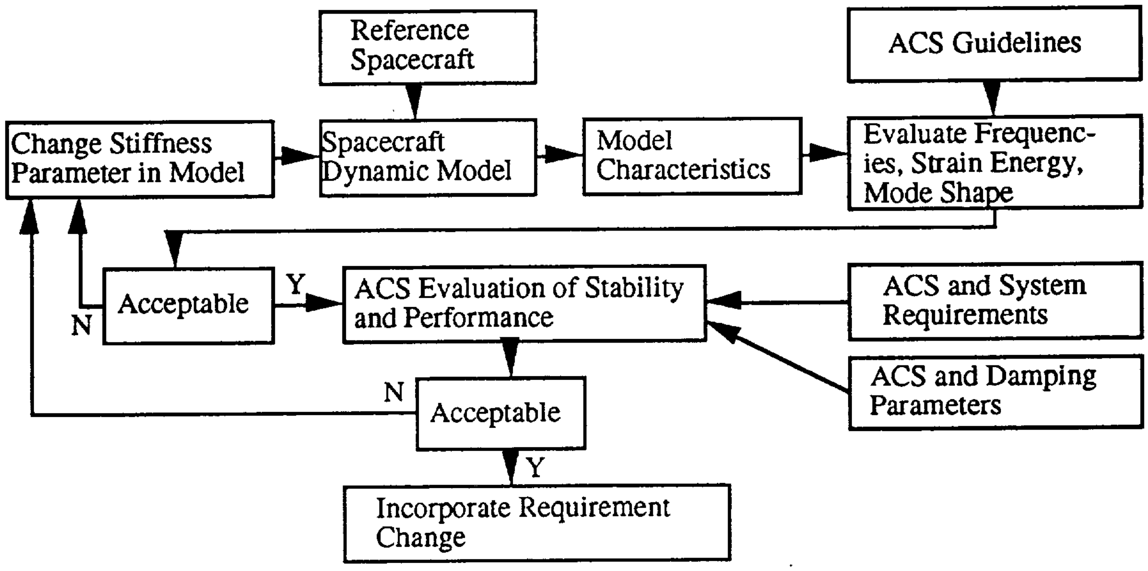

Figure 6. Initial Requirement Development Process

loop test is used to provide confidence in the functionality and compatibility of the control subsystem hardware and software and the model used in the verification simulation.

Performance verification by simulation offers several advantages over a ground based end-to-end performance verification test approach. In the test approach, allocation for test measurement errors erodes already stringent requirements, which compounds flight hardware design challenges. Additionally, if the flight hardware is state of the art, the test support requirements are potentially beyond state of the art or demand expensive precision. The simulation approach is cost effective: the investment is in understanding the root behavior of the flight hardware and its environment, and not in developing elaborate test equipment and environments. Finally, this process permits greater latitude in investigating performance under off-nominal conditions. This design and verification approach has been used on a control structural interaction testbed developed by TRW.

The Control Structural Interaction Testbed

The Precision Control of Agile Spacecraft (PCAS) project is a company funded Internal Research and Development program to investigate new design techniques to deal with future generations of NASA and DOD spacecraft (References 9, 14, 16, 17). These spacecraft will require a high level of agility and precision of line-of-sight (LOS) pointing. Simultaneous requirements on agility and pointing, as well as limits on size and weight present significant technical challenge for spacecraft designers. LOS control for these spacecraft will be needed typically over a wide range of motions (in both amplitude and frequency.) Submicroradian jitter requirements to satisfy payload performance must be balanced with large payload fields of view (i.e., 50 to 1000 microradians) and fields of regard (2 to 50 degrees.) In addition, many missions will have multiple gimbaled payloads that must maintain precise pointing despite large maneuvers of the main spacecraft and other appendages. Dynamic range and bandwidth considerations demand a dimensionally stable structure with multiple overlapping control subsystems. Many missions will require at least four levels of control: slew, attitude, shape, and vibration. The single -bay truss

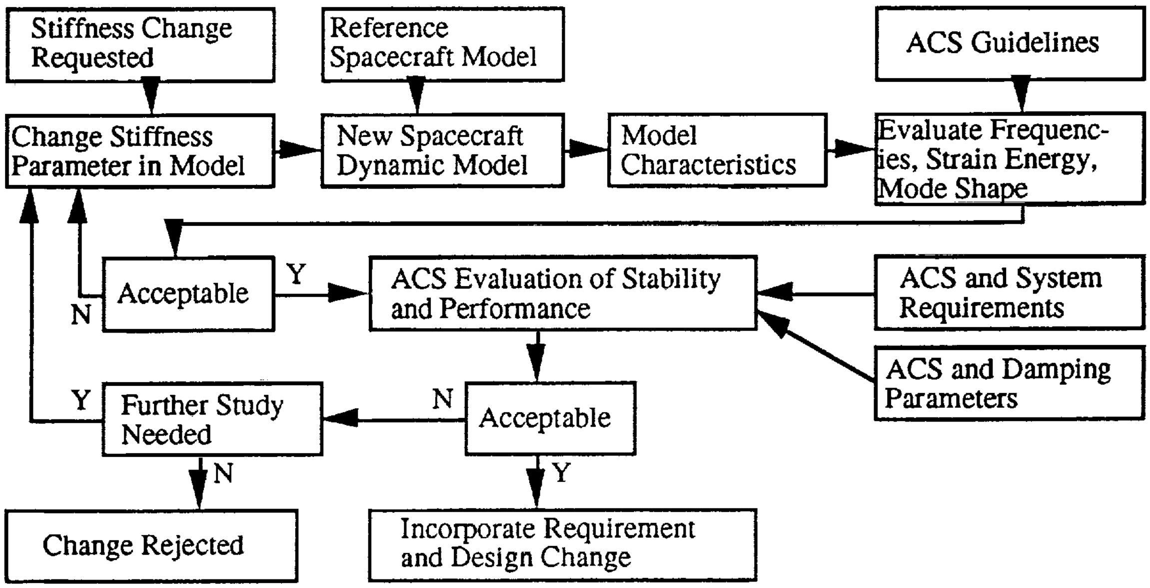

Figure 7. Stiffness Change Evaluation Process

structure (see Figure 9, Reference 4) used for many years of research needed to be recycled to provide a relevant testbed.

A mission analysis was performed to gather a set of requirements for the design of a control structural testbed test article. Candidate configurations were evaluated on the basis of proper scaling of flexible dynamics characteristics, strength, and versatility. A multi-bay truss mounted on a single axis air bearing (with provisions for mounting a flexible appendage) was selected for final detailed design. Conflicting requirements of high angular acceleration, low natural frequencies, and structural integrity were resolved through design iteration. Parameters traded included truss length and width, number of bays, member cross section, joint mass, and inclusion of gravity off-load guy wires.

Figure 10 shows the final truss configuration. The truss is long (18 feet) and narrow (10 inches) to provide low frequencies in the slew plane and higher frequencies in the vertical direction. NASTRAN modeling of the nominally loaded truss yielded a 5.5 Hz horizontal plane fundamental frequency and moment of inertia consistent with the required 4 degree per second per second slew angular acceleration. The truss has sufficient strength to support enough additional mass to reduce the horizontal plane fundamental frequency to the 4 to 5 Hz range, with some reduction in slew acceleration. Guy wires are used to raise the fundamental frequency in the vertical direction to 13.2 Hz while the backing structure provides moment balance and a platform for mounting a flexible appendage.

An evaluation of truss construction methods led to the selection of the patented STAR*NET Structures threaded hub system. This system allows easy interchange of the baseline aluminum structure with passive and active composite members. Control hardware, such as the Surface Accuracy Measurement System (SAMS) sensor targets, reaction wheels, and proof mass actuators, can also be placed at any bay of the truss. This modular design is ideally suited to

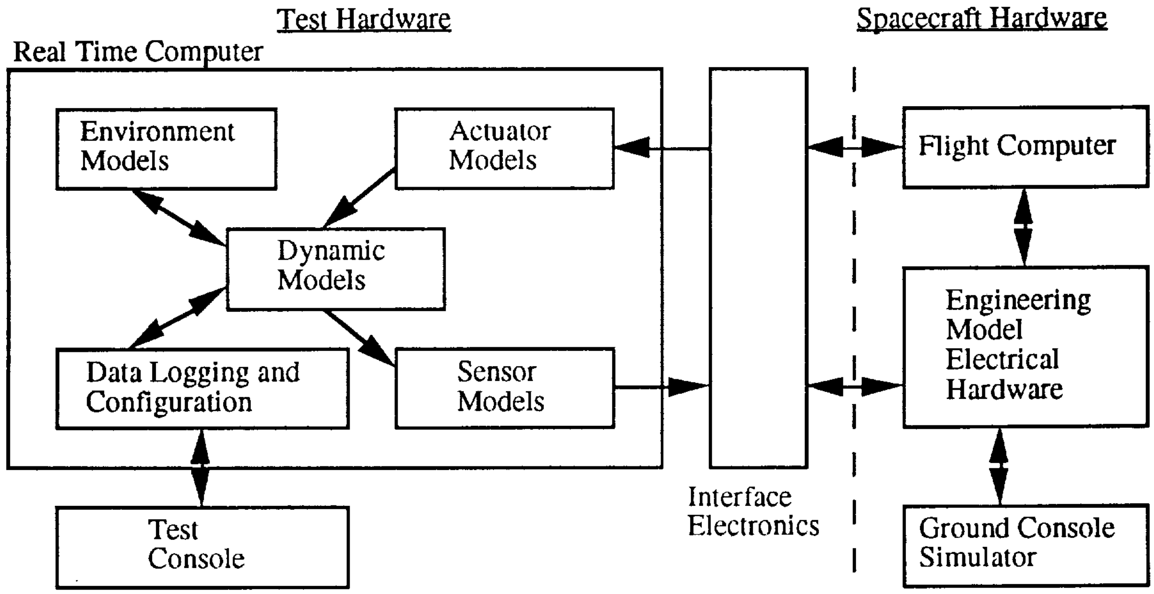

Figure 8. Hardware in the Loop Test Configuration

evaluation of a wide variety of structure and control concepts and allows realistic measures of sensitivity to structural parameters and sensor/actuator location.

Testbed control equipment, shown in Figure 12, is also configured for modularity and interchange ability. A Digital Equipment Corporation MicroVAX II computer hosts the test software and provides interfaces with the Structural Control Processor (SCP) and Numerix vector processor.

The SCP implements the very high bandwidth multi-input multi-output control laws for active vibration control using embedded piezo-ceramic actuators and sensors. The SCP is a TRW developed, flight qualifiable control computer based on 32-bit floating point digital signal processors, and is currently programmed to perform 12 parallel digital filters with sample rates of 2.8 kHz. The SCP has a maximum sample rate of 30 kHz. Adaptive active structural control capability is provided by a high speed serial link for real time update from either the MicroVAX or a PC to the SCP. Identification algorithms and control laws for the appendage and the truss actuators are implemented in the Numerix vector processor. Numerix supplied Analog to Digital (A/D) and Digital to Analog (D/A) cards are used to convert analog sensor inputs to a form suitable for the vector processor and to provide signals for the actuators. The digital input capability of the Numerix vector processor is expanded with a custom digital conditioning electronics assembly.

The truss is carried on a custom Anorad air bearing equipped with a 30 foot-pound peak torque brushless DC motor. Maximum acceleration is greater than 4 degrees per second per second with nominal truss inertia. Slews of up to 60 degrees can be accommodated with the 18 foot truss. The air bearing contains an optical encoder accurate to 1 microradian, which can be read by either the Numerix vector processor or the MicroVAX. Two SAMS sensors mounted on the truss allow relative deflection measurements of the truss during slew. A laser interferometer target is mounted on the truss endpoint to measure slew/settle residual motion.

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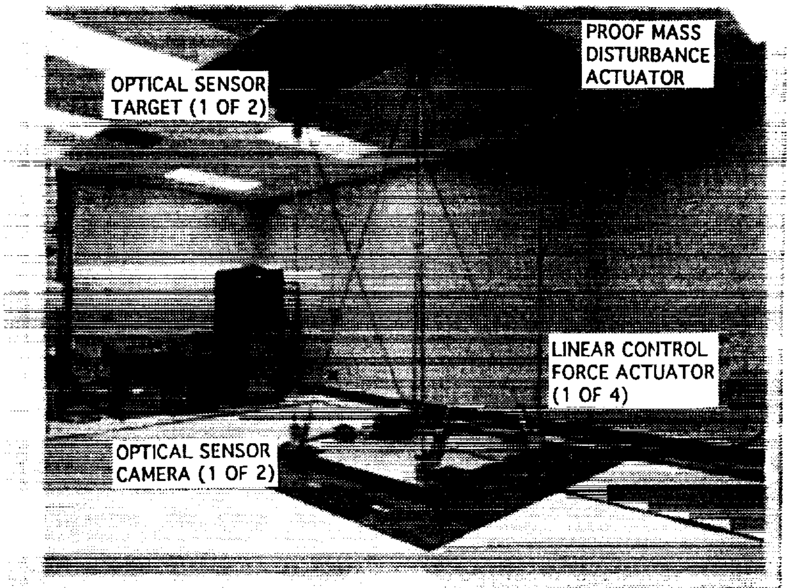

Figure 9. Single Bay Truss

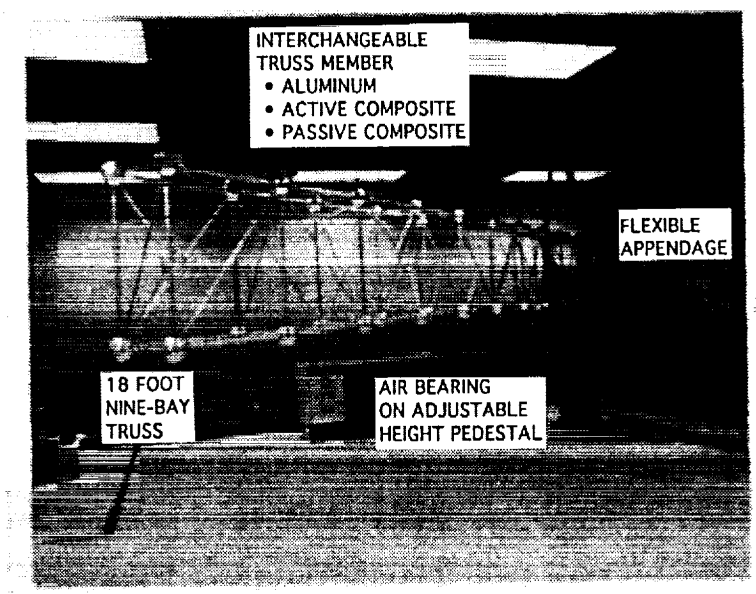

Figure 10. Control Structural Interaction Truss

The flexible appendage system, shown in Figure 12, is configured either for stand alone operation or as part of the multi-body truss. A complete drive system, including a 20 foot-pound peak torque Pacific Scientific brushless DC motor with resolver, motor controller, and computer interface was integrated in 1989. Use of a Ringfeder shaft locking assembly allows convenient interchange of the appendage structure. Presently attached to the drive is a 3 foot long flexible appendage fitted with a SAMS sensor. Four multiplexed light emitting diodes (LED) allow the

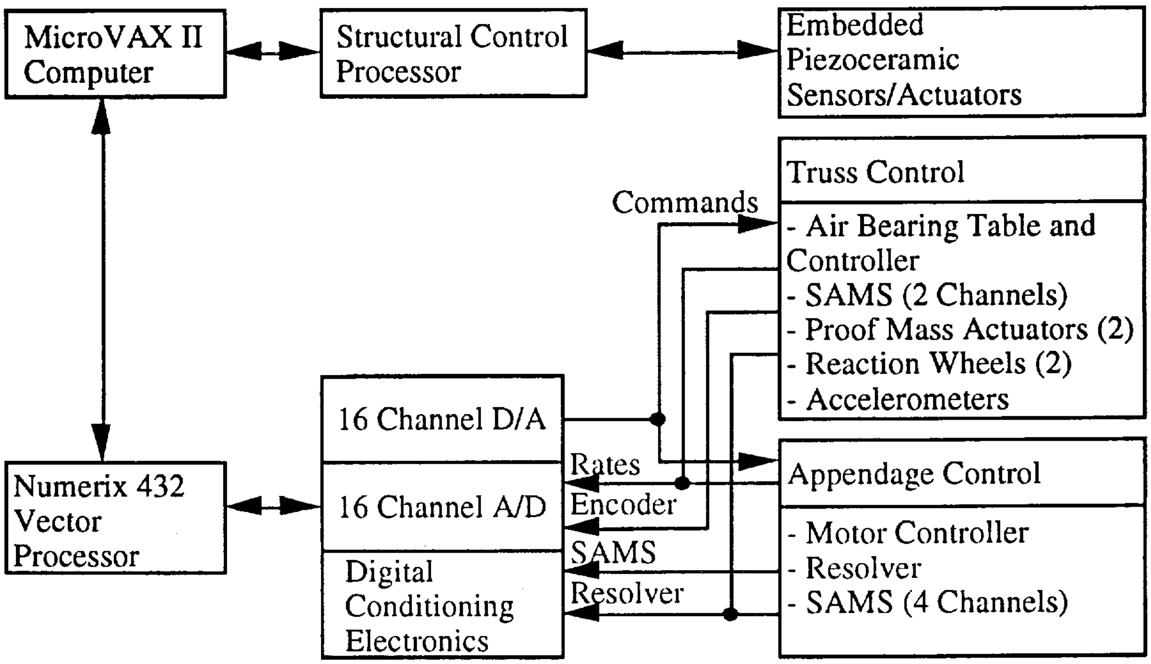

Figure 11. Control Structural Interaction Testbed Control Equipment

SAMS to measure the relative deflection of the appendage at four points along the length. A custom interface with the Numerix vector processor permits reading each LED position at a 250 Hz sample rate, for use in closed loop appendage control laws.

The completed test facility also includes testbed control equipment and measurement instrumentation. A Hewlett-Packard 16-channel modal survey system is used to provide detailed dynamic models of the testbed for either control design or identification algorithm verification. A Hewlett-Packard multi-axis laser interferometer system with 2 nanometer resolution allows structural deformation measurements during slew. A Kaman inductive position sensing system with 100-nanometer resolution provides high bandwidth measurements of residual vibration during the settle phase. A pneumatically isolated optical bench is provided to support the measurements for both truss and component tests.

To provide the test environment required for precision measurements, the facility is built around a 20 foot by 30 foot isolated seismic pad located in a dedicated test room. Adjacent to the test room is an equipment room and a computer/test operator room. Test room walls are treated to increase sound absorption and reduce stray and reflected light. Low velocity air conditioning equipment, separate from the house air conditioning plant, further reduces disturbance on the testbed. Sealed cable ports in the test room walls provide for electrical connections to the computer and equipment rooms, without introducing stray light or air currents.

Testbed Results

The testbed has been used to verify the simulation tools and models used in the precision flexible spacecraft integrated process. A system level modal survey, with multiple accelerometers, was performed to demonstrate the fidelity of the NASTRAN model and obtain accurate modal

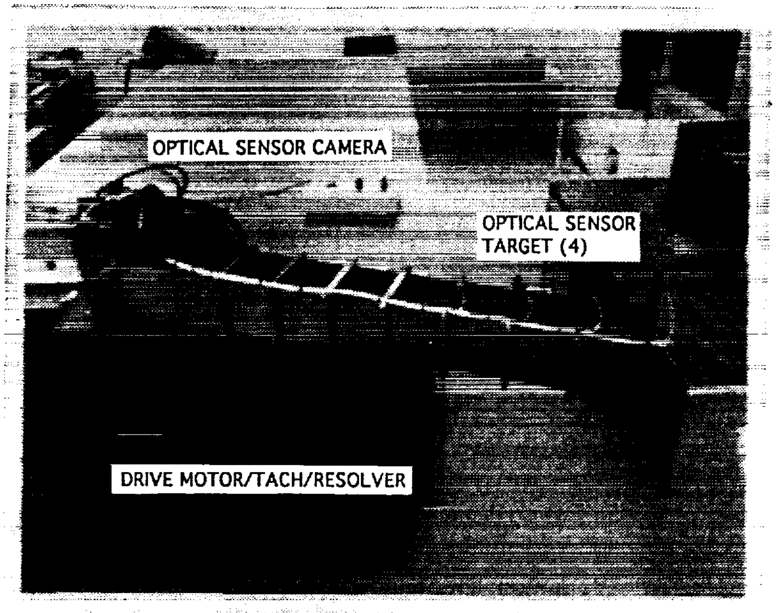

Figure 12. Flexible Appendage System

damping values. Component tests were conducted on the active members to characterize their low level creep and linearity. System level slew tests, with and without active members, were run to verify the assumptions made in the simulation and to understand the nature of the dynamic response.

Agreement between modal survey results and NASTRAN predictions was better than 10% for the first group of modes, and averaged better than 10% for the second group of modes. This level of agreement is satisfactory considering the lack of detail in the model in regard to joint stiffness and member preload from manufacturing and assembly variations in the truss members. Observed modal damping levels of a few tenths of a percent are typical of those expected from a threaded joint type of structure. Modal survey results were used to tune the NASTRAN model to reduce the errors in modal frequencies and mode shapes. Table 1 summarizes the results of the modal survey.

Active (embedded piezo-ceramic) composite member hardware models were verified by component tests. A test fixture was constructed to permit precision measurement of active member motions using the laser interferometer system. Short term and long term creep was measured by applying step changes in voltage to the active member actuators and observing the response with the laser interferometer. Very low values of creep were observed: responses were typically 95% complete in less than 0.1 seconds and 98% complete in less than 0.2 seconds, with total creep in the 1% to 2% range. Active member low level linearity was measured by applying a small sinusoidal voltage to the actuators and heavily filtering the laser interferometer measurement. Response remained linear, with no observable threshold effects, down to the 10 nanometer resolution of the laser interferometer optical configuration.

Performance verification of the testbed and the traceability of the simulation was proven by conducting system level static and slew tests. Multi-mode (horizontal plane, vertical plane, and torsion) active damping in the 10% to 20% range was demonstrated by inserting four active members in the truss at selected locations. Active damping control laws were implemented in the

Table 1. Modal Survey Test Results

Mode	Mode Description	NASTRAN Frequency (Hz)	Test Data Frequency (Hz)	Prediction Error (%)
1	Rigid Body	0.00	0.00	0.0
2	Horizontal Bending	4.79	4.64	3.1
3	Vertical Bending	5.36	5.85	9.1
4	Torsion	13.49	13.89	3.0
5	Vertical Bending	22.66	26.29	16.0
6	Horizontal Bending	38.43	34.05	11.4
7	Torsion	42.18	41.64	1.3

structural control processor sampling at 2.8 kHz. Slew control laws were implemented in the Numerix computer.

Figure 13 shows a comparison of simulation and test results for a typical truss slew case with a 3.5 degree slew in 2 seconds. A high level of correlation between simulation and test is seen during the slew phase. During the settle phase, both cases show similar level of ripple at the 6.4 Hz frequency of the first gain stabilized mode. The discrepancy in response during the early part of the settling was traced to unmodeled dynamics in the air bearing torquer, which will be corrected in the next model update. This demonstrates the value of modelling iterations, based on test results, to ensure valid simulations. However, since the airbearing is not part of the flight system, it also demonstrates the difficulty of removing all test artifacts from an end-to-end test.

Summary

TRW has developed a testbed that provides the critical capability to validate control system performance for multibody flexible structures for future NASA and DoD missions (high levels of agility, submicroradian jitter requirements, large structures). The testbed is easily reconfigurable and can be used to validate key models and simulation tools. The emphasis of the testbed design is to validate performance simulation tools required and is not intended as a complete ground-based end-to-end test.

This approach to testbed design is very cost-effective and flexible. TRW's methodology is based on a proven building block process whereby a combination of analysis, simulation and test has replaced end-end performance verification by ground test. Many advantages to this approach were described. In particular, the simulation approach grounded by appropriate hardware test data is cost-effective because the investment is in understanding the root behavior of the flight hardware and not in the ground test equipment and environment.

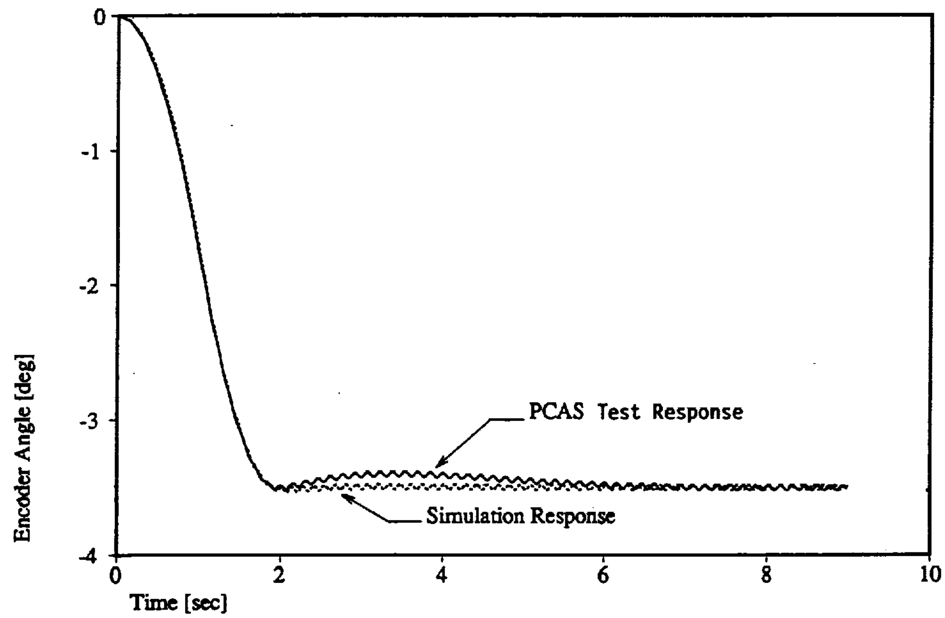

Figure 13. Response to Bang-Bang Slew Profile

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